MAE263F Project Proposal

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I. INTRODUCTION

Robot manipulation has long been dominated by rigid-link manipulators that achieve high precision and repeatability in structured environments such as manufacturing and assembly lines. These systems rely on well-defined kinematic and dynamic models to perform tasks with millimeter-level accuracy. However, their rigidity becomes a limitation in unstructured or dynamic environments, particularly where interaction with delicate or irregular objects is required. In contrast, soft robotic manipulators, composed of highly deformable materials such as silicone or elastomers, can passively adapt their shape to external forces, allowing for safer and more flexible interaction. The study of soft manipulators remains an ongoing research topic due to several challenges, such as difficulty of achieving accurate sensing and control for unknown environment. Despite these challenges, soft robotic manipulation has demonstrated promising applications in diverse fields such as minimally invasive surgery, agricultural harvesting, and marine exploration, where adaptability and gentle contact are paramount.

II. MOTIVATION

This project focuses on developing and simulating a soft robotic manipulator for underwater exploration, mounted in front of a submarine. The manipulator will perform tasks such as environmental monitoring, sample collection, and interaction with fragile marine organisms like corals or sponges. Traditional rigid arms are limited in such settings due to their inability to safely contact or adapt to irregular surfaces and their sensitivity to hydrodynamic disturbances. In contrast, a soft manipulator's compliance allows it to absorb fluid-induced forces and conform to its surroundings, making it inherently safer and more stable for trajectory tracking under uncertainty. The use of soft manipulators in underwater exploration could significantly enhance the precision and safety of data collection and specimen sampling, contributing to sustainable ocean research and reducing ecological damage during exploration missions.

The proposed system consists of a soft robotic manipulator mounted on a submarine, designed to maintain its end-effector position while the vehicle is stationary. Hydrodynamic forces generated by the flow field act on the manipulator, causing deformation and positional drift. The control objective is to maintain the desired end-effector position by actively adjusting the axial displacement (x) and bending angle (θ) of the manipulator's first node, similar to an inverted pendulum stabilization problem. The manipulator operates in an uncertain underwater environment affected by random disturbances such as local flow turbulence, gusts, and collisions with small obstacles. This setup represents a complex nonlinear control problem where the compliant structure must counteract fluid-induced motion while preserving trajectory stability and precision. Addressing these challenges requires accurate modeling of both the manipulator's elasticity and the external flow dynamics, as well as a robust control strategy capable of compensating for continuous disturbances.

III. LITERATURE REVIEW

Control of a soft robotic appendage is a well-studied challenge, with multiple simulation approaches developed to predict motion under external forces and control inputs. Burch et al. (2020) modeled a soft appendage using a planar discrete elastic rod to analyze its swinging motion around a fixed point. Their hybrid control design used separate controllers for upward equilibrium stabilization and for driving the appendage back into position. While their model operated in air and ignored fluid dynamics, the control strategy offers valuable insights for stabilization in dynamic environments. The present project extends this concept into an underwater setting, where hydrodynamic forces dominate. Instead of stabilizing a static equilibrium, the goal is to maintain the end-effector position under continuous flow disturbances, emphasizing continuous feedback control rather than hybrid switching.

Similarly, Scott et al. (2020) applied planar discrete elastic rod modeling to simulate eel-like underwater locomotion. Their work introduced internal damping and explored various hydrodynamic modeling approaches but assumed a stationary fluid. In contrast, the proposed system will operate within time-varying ocean currents, requiring stabilization under external flow disturbances. Although Scott et al.'s study focuses on locomotion rather than manipulation, it provides useful insights into underwater dynamics and the impact of fluid–structure interactions, which are directly applicable to the proposed underwater manipulator.

Many applications propose utilizing pneumatic or hydraulic actuation for controlling the robot to take advantage of the soft links (Phillips et al., 2018; Shen et al., 2020). This will lead to novel actuation methods for the robot where each node in a discrete elastic rod model can be actuated. This leads to an extension where the proposed study can look at the effects of disturbances on a manipulator in motion.

In the most fascinating paper, a neural controller can be used to abstract the minutiae of a control algorithm (Tong et al., 2024). The main model used will still be a discrete elastic rod in a manner similar to that proposed in the paper. Combining the novel actuation methods presented in previous papers with the control optimization methods for deformable linear objects in this paper, there can be an extension looking into integrating a neural control scheme to have the appendage move to a target location under load.

IV. PROPOSED APPROACH

A. Simulation Framework

The soft manipulator will be modeled as a planar discrete elastic rod, following a finite-segment approximation similar to the bending-rod formulation used in previous homework implementations. The manipulator consists of N nodes connected by $N-1$ elastic segments, each represented by its Cartesian coordinates $q = [x_0, y_0, x_1, y_1, \ldots, x_{N-1}, y_{N-1}]^\top$. The simulation is implemented in Python and integrates the system dynamics via an implicit Euler scheme with Newton–Raphson iterations.

B. Elastic Energy Formulation

Each element of the soft manipulator experiences both stretching and bending deformation. The total potential energy E is expressed as the sum of stretching (E_s) and bending (E_b) energies:

$$E = \sum_{k=1}^{N-1} E_s^{(k)} + \sum_{k=2}^{N-1} E_b^{(k)}. \quad (1)$$

The **stretching energy** between nodes k and $k+1$ is given by:

$$E_s^{(k)} = \frac{1}{2} EA\, l_k \left(1 - \frac{\|\mathbf{e}_k\|}{l_k}\right)^2, \quad (2)$$

where EA is the axial stiffness, l_k is the rest length, and $\mathbf{e}_k = \mathbf{x}_{k+1} - \mathbf{x}_k$.

The **bending energy** at node k depends on the discrete curvature κ_k:

$$E_b^{(k)} = \frac{1}{2} \frac{EI}{l_k} (\kappa_k - \bar{\kappa}_k)^2, \quad (3)$$

where EI is the bending stiffness and $\bar{\kappa}_k$ is the natural curvature. The discrete curvature is computed as:

$$\kappa_k = \frac{2\, \mathbf{t}_{k-1} \times \mathbf{t}_k}{1 + \mathbf{t}_{k-1} \cdot \mathbf{t}_k}, \quad (4)$$

with $\mathbf{t}_k$ being the unit tangent vector along edge k.

C. Equations of Motion

The nodal dynamics follow Newton's second law, including inertial, elastic, viscous, and external (gravitational and buoyant) forces:

$$\mathbf{M}\ddot{q} = \mathbf{F}_{\text{elastic}}(q) + \mathbf{F}_{\text{viscous}}(\dot{q}) + \mathbf{W}, \quad (5)$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{F}_{\text{elastic}} = -\nabla E$, $\mathbf{F}_{\text{viscous}} = -\mathbf{C}\dot{q}$ represents hydrodynamic drag, and $\mathbf{W}$ combines weight and buoyancy effects.

To advance the system in time, the dynamics are integrated using the Newmark–Beta method, which provides second-order accuracy while avoiding the excessive numerical damping commonly observed in the fully implicit Euler method. This choice is particularly important in underwater simulations, where preserving the natural oscillatory response of the manipulator is necessary to accurately capture the effects of ocean currents and flow-induced vibrations.

Given displacements q_n, velocities $\dot{q}_n$, and accelerations $\ddot{q}_n$ at time step n, the method updates the state at $n+1$ according to:

$$q_{n+1} = q_n + \Delta t\, \dot{q}_n + \frac{\Delta t^2}{2}\left[(1 - 2\beta)\ddot{q}_n + 2\beta\, \ddot{q}_{n+1}\right], \quad (6)$$

$$\dot{q}_{n+1} = \dot{q}_n + \Delta t\left[(1 - \gamma)\ddot{q}_n + \gamma\, \ddot{q}_{n+1}\right], \quad (7)$$

where β and γ are the integration parameters that determine stability and numerical damping. In this project, we use $\beta = 0.25$ and $\gamma = 0.5$, corresponding to the constant-average-acceleration scheme, which ensures unconditional stability while preserving the dynamic response fidelity.

Substituting the above relations into the equilibrium equation yields the nonlinear residual at time t_{n+1}:

$$\mathbf{R}(q^{n+1}) = \mathbf{M}\ddot{q}^{n+1} + \mathbf{C}\dot{q}^{n+1} + \mathbf{F}_{\text{elastic}}(q^{n+1}) - \mathbf{W} = 0, \quad (8)$$

which is solved iteratively to find q^{n+1} and $\dot{q}^{n+1}$.

D. Control and Boundary Conditions

The base of the manipulator is fixed to the submarine body, while the distal end effector is controlled to maintain a target position. The control input adjusts the first node's position (x) and orientation (θ) to counteract deflection caused by fluid flow and disturbances. A proportional–integral–derivative (PID) controller minimizes the trajectory error:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{de(t)}{dt}. \quad (9)$$

The system resembles an inverted pendulum, where maintaining end-effector stability requires feedback on both position and angle.

E. Hydrodynamic Disturbances

The surrounding fluid exerts drag forces proportional to the relative velocity between the manipulator and the flow:

$$\mathbf{F}_d^{(i)} = -\frac{1}{2}\rho C_d A \mathbf{v}_{\text{rel}}^{(i)} \|\mathbf{v}_{\text{rel}}^{(i)}\|, \quad \text{with} \quad \mathbf{v}_{\text{rel}}^{(i)} = \dot{\mathbf{x}}_i - \mathbf{u}_{\text{flow}}. \quad (10)$$

Here ρ is fluid density, C_d is the drag coefficient, and $\mathbf{u}_{\text{flow}}$ is the local flow velocity induced by ocean currents and manipulator velocities.

F. Simulation Development Pipeline

The simulation of the underwater soft robotic manipulator will be developed progressively in four main stages to ensure physical accuracy, numerical stability, and scalability toward a full ocean current environment.

1) **Viscous Medium Under No Load:** The first stage involves modeling the manipulator in a quiescent, viscous fluid without external flow. This setup isolates the effects of internal elasticity, damping, and controller behavior in a stable environment. The viscous term in the damping matrix $\mathbf{C}$ is retained to simulate fluid resistance, allowing verification of the manipulator's baseline dynamics and convergence of the Newmark–Beta integration scheme.

2) **Constant External Load:** In the second stage, a uniform distributed load is introduced along the manipulator to represent a simplified, constant ocean current. This load acts tangentially along the manipulator's length and generates steady-state deflection. By simulating multiple constant load magnitudes, we can analyze how varying hydrodynamic pressure affects trajectory tracking and structural deformation. This step also provides a controlled framework to tune controller gains (K_p, K_i, K_d) for stable operation under static flow conditions.

3) **Dynamic Ocean Current Model:** The third stage incorporates a spatially and temporally varying ocean current model, defined in equation 10. This stage evaluates the manipulator's transient response to realistic underwater disturbances. The results will illustrate how the soft manipulator adapts to and compensates for time-varying hydrodynamic conditions while maintaining end-effector stability.

4) **Extension to Three-Dimensional Modeling:** Once validated in two dimensions, the system will be extended into a full 3D framework to capture spatial bending and gravitational effects underwater. The model will be reformulated using spatial vectors $q = [x_i, y_i, z_i]^\top$ for each node, and the elastic energy terms will be expanded to include out-of-plane curvature and twist. This 3D implementation will enable future integration with submarine-mounted robotic systems for more realistic trajectory tracking and sampling tasks in complex ocean environments.

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